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# A PERSPECTIVE ON HYDROLOGIC PREDICTION TRENDS

D. L. Fread*
Director
Office of Hydrology, National Weather Service, Silver Spring, MD

## 1. INTRODUCTION.

Floods are the leading weather related hazard throughout the world. A review of the world's recent and prominent flooding events remind us that major floods will continue to occur and are devastating. Preparedness for these events can lead to saving lives and property. Within the USA alone, floods cause an average of $3.6 billion in damages and 131 lost lives annually (Stallings and Fread, 1997); over 75 percent of the Presidential disaster declarations for the USA are in response to flooding events. Droughts, while generally not life-threatening in the USA, have a serious impact on agriculture, ecosystems and water management, and the economy in general. Therefore, it is imperative to make the mitigation of both floods and droughts a high-priority task.

Benefits associated with hydrologic forecasts are attributed to both structural and nonstructural actions. In the USA, the principal structural solution to flood damage reduction is reservoirs and levees while the primary nonstructural means is timely and accurate hydrologic forecasts. Hydrologic forecasts, however, are only of value if they induce a response from the floodplain user that leads to an effective action. For example, when the flood warning is issued to the general public through appropriate dissemination channels, a benefit can only accrue through evacuations, flood-fighting measures, or shutdown of facilities to reduce potential flood losses.

*Corresponding author address:
Danny L Fread, Office of Hydrology,
NWS, 1325 East-West Hwy,
Silver Spring, MD 20910
Telephone 301-713-1658, Fax 301-713-0963,
e-mail: Danny.Fread@noaa.gov

The USA weather program has been providing river and flood forecasts for the public since 1890. These forecasts have typically been provided to emergency managers and the general public for the protection of life and property in the vicinity of rivers. The principal economic benefits associated with hydrologic forecasts are related to flood mitigation. However, hydrologic forecasts of river levels and inflows to reservoirs also are extremely valuable and produce substantial annual benefits to water resources decision makers in operation of projects for water supply, navigation, hydroelectric power generation, irrigation, and recreation. They have also been used for the assessment of extended drought scenarios. Many federal, public, and private sectors are calling for more detailed river forecast information with increased precision over space and time. To meet these needs, the National Oceanic and Atmospheric Administration (NOAA), National Weather Service (NWS) is capitalizing upon its modernization activities in remote sensing, data automation, computer upgrades, graphical dis-plays, and advanced hydrologic/hydrometeorologic modeling capabilities. These same hydrologic modeling advancements could also be beneficial to water facility designers.

## 2. EXPANDING REQUIREMENTS FOR NWS HYDROLOGIC SERVICES

"The Great Flood of 1993" in the Midwest heightened the Nation's awareness of the devastation and strife that floods can impose upon society and the environment (NWS, 1994). With this heightened awareness, subsequent floods have reminded us that extreme events will continue to occur, e.g. the recent flooding along the Red River of the North and the recent floods in California, the Northwest, and the Ohio Valley. Furthermore, structural modifications to the riverine environment and flood proofing flood prone areas are not always viable solutions. Therefore, as society continues to experience population growth and people choose to live by the water, we have an ever increasing need to improve our predictions to support flood and drought mitigation activities.

Looking toward the 21st century, individuals have an increased awareness of the need to live in harmony with the environment; thus, the recent enhanced use of the term, "sustainable development" (President's Council on Sustainable Development, 1996). Within this context, the importance of water resources for all hydrologic regimes is increasing. For example, within the USA, we find competing demands for the allocation of water among its users (i.e., fisheries, irrigation, hydropower and municipalities). This increase in demand for water looms as a national problem that requires improved water quantity forecasts for sustainable use.

To meet these requirements, the NWS is committed to the development and implementation of an Advanced Hydrologic Prediction System (AHPS) capable of producing hydrologic forecasts with lead times of a few days to several months. Such forecasts will greatly improve the Nation's capability to take timely and effective actions to mitigate the effects of floods, and the forecasts will also provide significant improvements in the type and quality of hydrologic information that is used to manage the Nation's water resources. The AHPS builds upon: partnerships with other water cooperators (federal, state, multi-state, quasi-governmental and private sector organization); the NWS infrastructure, including the 13 RFCs and the NWS River Forecast System (NWSRFS), a very large software system used by RFC hydrologists to produce forecasts of discharge or stage time series at selected locations (approximately 4,000 along the Nation's rivers); and the NWS Modernization, which is providing NWS RFCs with Advanced Weather Interactive Processing System (AWIPS) hardware, a powerful suite of networked computer workstations with graphic capabilities. The modernization of the NWS is also providing coverage of the USA with approximately 140 WSR-88D Doppler radars, which provide the basis for multi-sensor, high resolution (space and time) precipitation estimates.

Advancements in the NWS hydrologic services program (Fread, 1996) are now being made by: 1) making critical software enhancements to the NWSRFS; 2) developing a NOAA Hydrologic Data System (NHDS); 3) increasing the use of short- to long-range quantitative precipitation/temperature forecasts and climate predictions within the NWSRFS through appropriate hydro-meteorological coupling algorithms; 4) effectively calibrating and implementing at each RFC advanced hydrologic/hydraulic models within the NWSRFS; 5) implementing an enhanced snow estimation and updating system (SEUS) that provides gridded estimates of snow water equivalent; and 6) providing more timely, accurate and informative forecast products ( Braatz, et. al., 1998 and NWS, 1997) to government and quasi-government water and emergency managers.

## 3. ENSEMBLE VERSUS DETERMINISTIC FORECASTING

The NWS River Forecast Centers (RFCs) typically issue deterministic stage forecasts for only one, two and three days into the future at most forecast points and crest forecasts out to about one week for a few selected forecast points. These forecasts are primarily produced with only historical and real-time data; however, in some cases 24 hour quantitative precipitation forecasts (QPFs) are used. In order to increase lead times of real time forecasts, it is critical to include future temperature and precipitation forecasts at all time scales out to seasonal. Enhancements to river forecasting include the combined use of deterministic and probabilistic procedures through Monte Carlo type simulations, i.e., the Ensemble Streamflow Prediction (ESP) technique (Day, 1985) of the National Weather Service (NWS).

ESP is one significant portion of the NWS River Forecast System (NWSRFS) as it produces an ensemble of possible streamflow hydrographs which can be analyzed using standard statistical techniques to generate forecasts. As a part of the NWS effort to modernize its hydrologic forecasting services, the ESP analysis and product generation capability of NWSRFS has been updated. And, a new program called the ESP Analysis and Display Program (ESPADP) has been developed so that forecasters may now use a Graphical User Interface to select products and review forecasts. With ESPADP, a wide variety of data may be analyzed in the ESPADP program, including: stage, flow and precipitation.

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ESP is run to produce an ensemble of stages for each forecast point. ESP, in it's basic form, assumes that historical meteorological data are representative of possible future conditions and uses these as input data to hydrologic models along with the current states of these models obtained from the forecast component of the NWSRFS. A separate streamflow time series is simulated for each year of historical data using the current conditions as the starting point for each simulation. The streamflow time series for each year's simulation can be analyzed statistically for peak flows, minimum flows, flow volumes, etc., for any future time period to produce a probabilistic forecast for the streamflow variable. This analysis can be repeated for different forecasts periods and additional streamflow variables of interest. Short-term quantitative forecasts of precipitation and temperature can be used to weight the years of simulated streamflow based on the similarity between the climatological conditions of each historical year and the current year. ESP allows flexibility in the streamflow variables which can be analyzed, the capability to make forecasts over both short and long time periods, and the ability to incorporate forecast meteorological data into the procedure.

In summary, to forecast with the ESP technique, an ensemble of possible streamflow hydrographs are calculated by initializing hydrologic models with the current states of the hydrologic system and then calculating hydrographs with those models using historical precipitation and temperature time series. A distribution is then fit to a sample taken from this ensemble of streamflow hydrographs for a specified time period. The fitted distribution describes the likelihood of an event occurring during the specified window in time. It is from this fitted distribution that forecast products are derived.

An enhanced method for calculating the ensemble of streamflow forecast has recently been developed. This method integrates long-range meteorological forecasts into the streamflow forecasts. The method consists of shifting the historical precipitation and temperature time series by daily $\lambda$ values prior to using them as input to the hydrologic models. The daily $\lambda$'s were calculated from the 2- to 6-day NWS Hydrometeorological Prediction Center precipitation and temperature forecasts, the 7- to 11-day NWS Climate Prediction Center (CPC) precipitation and temperature forecasts, the 1-month climate outlook from CPC, and the seasonal climate outlooks from CPC. The local NWS Weather Forecast Office (WFO) produced 24-hour QPFs may also be blended into the ESP forecasts.

A significant contribution of ensemble forecasting, in contrast to deterministic forecasts, is the resulting capability to assess "what if" scenarios using the resulting exceedance probability information. For example, should a flood fight be eminent and the question be raised regarding the height to which sand bags should be placed, the answer can be derived with consideration of the information provided by a probability of exceedance plot (Braatz, et. al., 1998 and NWS, 1997). Using this type of a real-time generated product, along with existing deterministic forecasts, an elevation which corresponds to an acceptable level of risk may be selected - an acceptable level of risk may be considered synonymous to the conditional probability of exceedance. This same type information may be incorporated in other applications as well, e.g., maximizing hydropower production.

A major advantage derived from the use of probabilistic forecasts is the knowledge gained from the expression of the uncertainties. With the awareness of the associated uncertainties, decision makers can use risk-based approaches. In addition to emergency managers, these decision makers may be water facility managers or designers who can benefit from this information which incorporates initial state conditions, i.e., historical/real-time precipitation and soil-moisture.

## 4. METEOROLOGICAL COUPLING

ESP, along with the coupled use of probabilistic meteorologic and climatologic predictions, provides a seamless suite of short (hours, few days) to long (several days, months, seasons) lead-time river forecasts in a real-time forecasting mode. The forecasts account for the hydrologic uncertainties in model structure and model parameters, as well as the inherent uncertainties of the meteorologic/climatologic predictions. The NWS is moving toward this new forecasting approach through implementation of the Advanced Hydrologic Prediction System (AHPS). These coupled forecasts are beneficial to critical mitigation decisions associated with flood and droughts. Extended (lead times out to weeks and months) river forecast implementation throughout the Nation will also benefit water resource managers in decision making for water supply, agriculture, navigation, hydropower and ecosystems.

As stated previously, within the basic ESP technique, an ensemble of possible streamflow hydrographs are calculated by initializing hydrologic models with the current states of the hydrologic system and then calculating hydrographs with those models using historical precipitation and temperature time series. The NWS is now enhancing the ESP technique to more directly include NWS meteorologic and climatologic forecasts. However, uncertainties of meteorologic forecasts tend to increase significantly with lead time; these uncertainties must be accounted for in order to use them. With this awareness, the ensemble generation technique still permits historical precipitation time series to dominate the ensemble domain at the longer lead times; and, precipitation and climate forecasts are incorporated in the ensemble generation with relative influence as conceptually indicated in Figure 1. This figure shows that members of the precipitation ensemble more nearly resemble historical climate experience as forecast lead time increases and as the skill of meteorological forecasts decreases. As the skill of meteorological forecasting produces more realistic ensemble members, the position of the curves in Figure 1 will move out in time.

Different sources of meteorological forecasts are used as input to produce the future precipitation ensemble. WFO forecast information is emphasized for the near-term (one to three day) time frame. At the present, this is a deterministic QPF forecast; probabilisitc QPFs (PQPFs) are being developed and will be used in the future. These PQPFs will control an ensemble precipitation processor that will generate ensemble members which account for hydrologically relevant space/time variability using historical precipitation to help limit extreme occurrences. For the long-range time scale, ensemble members depend on probabilistic products from the Climate Prediction

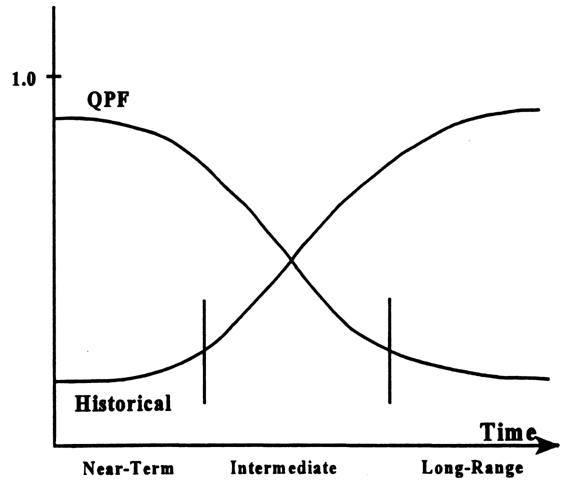


Figure 1. Incorporation of precipitation data types through time for continuous hydrologic forecasting.

Center (CPC) that are used to rescale historical precipitation events. In the intermediate range, techniques are being developed to make use of ensemble products that will be produced by different NCEP models over the full range of time scales, with appropriate adjustment to remove biases using historical precipitation and with additional modifications by forecasters.

## 5. MODEL COMPONENTS FOR THE FUTURE

Further advancements which appear promising in operational hydrologic forecasting include: 1) the application of distributed hydrologic models; 2) implementation of dynamic distributed flow routing models to account for the effects of bridges, levee failures, and backwaters; and 3) enhancements which better enable the modeling of physical processes, such as streamflow resulting from snowmelt during dynamic temperature, humidity, and wind conditions. These advancements make use of the emerging distributed precipitation data resulting from the WSR-88D radars, satellite information and GIS-based data systems; the latter providing information regarding topography, soil ~~moisture~~ type, land use, etc.

Although various distributed hydrologic models have been topics of research for greater than four decades, if has been the very recent availability of two distributed data sets that has invigorated their enhancement and application in operational forecasting (Smith, et. al., 1996; Finnerty, et. al., 1997). These two data sets are namely the NWS WSR-88D distributed precipitation in the form of four (4) kilometer by four (4) kilometer girds (with future two (2) kilometer by two (2) kilometer grids) and GIS-based system applications. The use of these tools and data sets are essential for real-time forecasting operations; however, prior to their effective application in a distributed hydrologic modeling environment, issues to be resolved include:

- What is the relationship between the spatial and temporal resolution of a distributed hydrologic model and the effectiveness of its operational application?
- What is the relationship between the modeled watershed's size and runoff characteristics and the effectiveness of a higher resolution distributed forecasting application?
- Since hydrologic models are best calibrated against multiple runoff events, what is the relationship between a model calibrated with longer historical time series of gaged data and the use of higher resolution but only a few years of radar data?
- Can new hydrologic models be developed which apply this high resolution data more directly and yet be efficient in its implementation and operation?

If a modified application of an existing distributed model be attempted, or a new model be developed, the developer has three essential components to consider. These components are: 1) rainfall abstraction as this provides the <u>volume</u> of available flow, 2) overland flow and interflow routing which corresponds to the <u>timing</u>, or rate, of the surface runoff, and 3) streamflow <u>routing</u>. An operational hydrologic model may account for each of the three components (volume, timing, and routing) by a psuedo-physical model or an alternative conceptual approach. The distributed model should be applicable and verifiable for many different watersheds, as well as many events. Of greatest importance, the distributed model(s) must be capable of real-time forecasting applications at NWS RFCs and WFOs. RFC applications will incorporate gaging station data, while some WFO applications must perform in the absence of gaging station data and provide site specific and categorical forecasts of flooding conditions.

Other promising deterministic forecast model improvements include dynamic distributed flow routing (Fread and Lewis, 1988) which best accounts for spatial and temporal streamflow variations resulting from: flow obstructions, i.e., bridges, backwater effects such as those which can occur at river confluences or the approach to a reservoir, channel storage changes resulting from levee overtopping or failure (including downstream return flows that may result from an overtopped/failed levee) , unsteady flows resulting from dam breaks, or hurricane storm surges. This list is not inclusive; however, it does indicate the enhanced capabilities that can be utilized in river forecasting for dynamic conditions. Use of this dynamic distributed flow routing, coupled with ESPADP and newly developed inundation mapping capabilities, provides for a spatial display of either inundation depths or probabilistic contours (zones) of inundation for a specified future window of time (NWS, 1997).

The third area of enhancement for future model components to improve streamflow forecasts is the continuing requirement to better model basic physical processes within the hydrologic cycle. For example, since the water supply of the western USA is influenced by snowmelt, it is extremely important to accurately determine the water equivalent of the snow cover. And, in an operational hydrologic forecasting setting, being able to model the timed contribution of snowmelt is necessary. The NWSRFS contains a snow model (Anderson,1973) which estimates the snowmelt (water equivalent) contribution to runoff. This computation is a function of air temperature. Improvements to the snow model will likely result if radiation is used rather than air temperature as an indicator of the energy flux; and, a more physical accounting is made for factors such as wind and humidity effects. The importance of accounting for these factors which contribute to snowmelt is highlighted by the January 1996 floods in the Northeastern USA in which an extremely large and rapid snowmelt occurred due to a highly abnormal combination of air temperature, humidity, and winds (Anderson and Larson, 1996).

## 6. SUMMARY

The NWS is actively pursuing the advancement of it's hydrological services program. These advancements are being built upon NWS modernization activities in remote sensing, data automation, computer upgrades, graphical displays, and advanced hydrologic/ hydrometeorologic modeling. The continuing requirement for these advancements is to provide the best forecasting service, in line with available technology, which will save lives, ~~and~~ protect property. In order to meet this requirement, the NWS is actively aiming to:

- Provide advanced hydrometeorologic/ hydrologic modeling procedures that better account for the natural and man-made complexities of the nation's river basins;
- Implement the NWS Ensemble Streamflow Prediction (ESP) procedure (Day, 1985) in order to provide probabilistic hydrologic forecasts into the future from weeks to months;
- Couple meteorologic forecasts at all time scales within the ESP procedure;
- Implement dynamic streamflow modeling in river reaches with significant dynamic effects caused by backwater, levee overtopping, or other transient phenomena; and,
- Provide advanced products (e.g., probability of occurrence information and inundated area mapping) for water resources management activities to other federal, state and local organizations.

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